CHAPTER 2

WEATHER RADAR

INTRODUCTION

Since the late 1940's, radar has been used to track weather systems. Subsequent advances were made in radar transmitters, receivers, and other system components. However, with the exception of transistor technology, few changes were made to basic weather radar systems through the 1970's. In the late 1970's, work began on the "next-generation" of weather radar (NEXRAD) using *Doppler* technology. The use of Doppler technology enabled weather radar systems to not only detect meteorological targets with greater detail, but also measure target motion and velocity. By the mid 1980's, a new weather radar that used this technology was introduced. This system is known as the weather surveillance radar-1988-Doppler, or WSR-88D.

WSR-88D systems have been installed at several Navy and Marine Corps shore-based weather stations. Even if you do not have a WSR-88D at your command, almost all weather radar information you will receive is derived from Doppler radar. Thus, it is important that you understand basic Doppler theory and the WSR-88D system.

In this chapter we discuss the Doppler weather radar (WSR-88D). We begin with a general explanation of electromagnetic energy and radar propagation theory followed by a discussion of Doppler radar principles. We will then concentrate on the configuration and operation of the WSR-88D system. Finally, we complete the chapter with a discussion of the advantages and limitations of WSR-88D products, and the publications associated with the system.

ELECTROMAGNETIC ENERGY

LEARNING OBJECTIVES: Describe the properties of electromagnetic energy. Define electromagnetic wave, electromagnetic spectrum, wavelength, amplitude, frequency, and Rower.

Understanding the fundamentals of electromagnetic (EM) energy will enhance your ability to use weather radar. No matter how sophisticated the radar system, theoretical limitations always exist. This background knowledge will also help you to understand the operation of the WSR-88D and to effectively use the products it produces. In the following text, we will begin with a general discussion of electromagnetic energy followed by a description of several properties related to electromagnetic waves.

ELECTROMAGNETIC WAVES

As discussed in chapter 1 of this module, all things (whose temperature is above absolute zero) emit radiation. Radiation is energy that travels in the form of waves. If this energy were visible, it would appear as *sine* waves, with a series of troughs and crests (fig. 2-1). Because radiation waves have electrical and

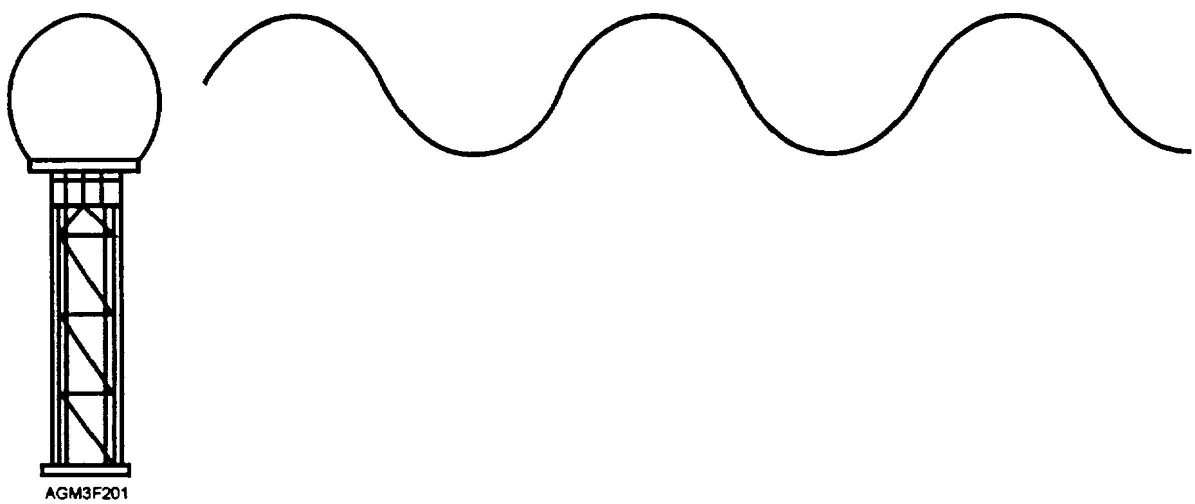


Figure 2-1.—Electromagnetic energy as sine waves.

magnetic properties, they are called *electromagnetic waves.*

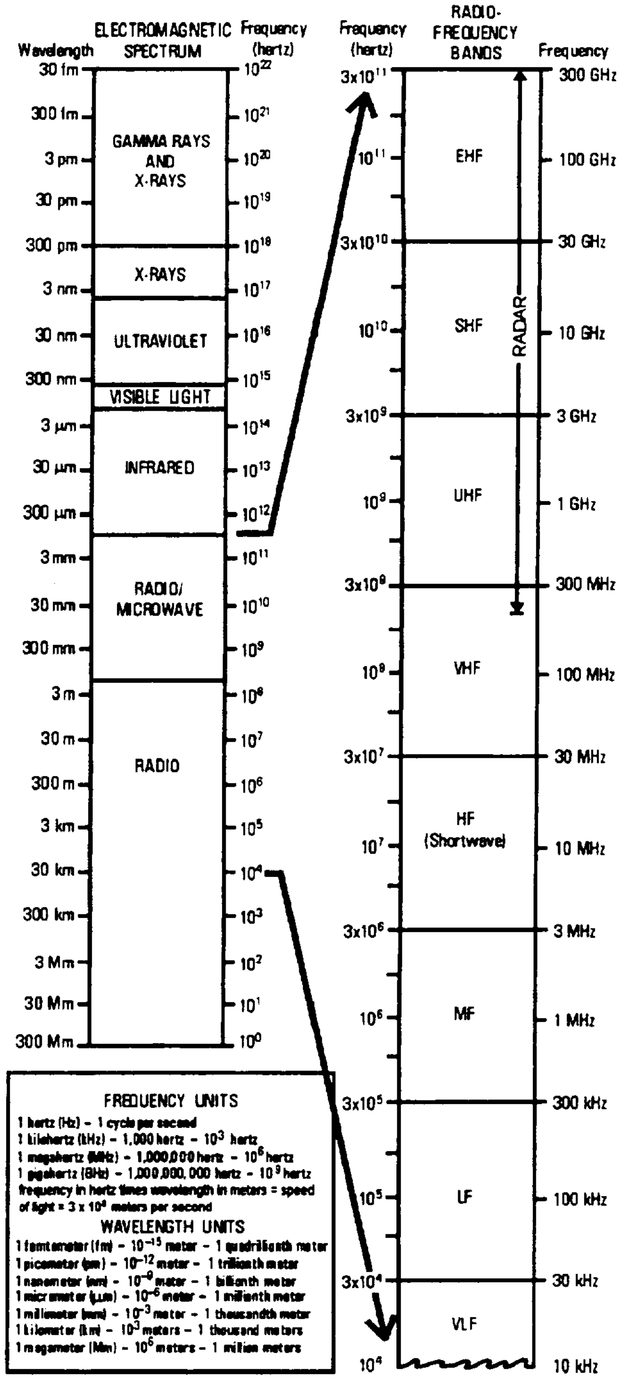
Most of the electromagnetic energy on the earth originates from the sun. The sun's electromagnetic waves propagate through space and into the earth's atmosphere. The sun actually radiates electromagnetic energy at several different wavelengths and frequencies, ranging from gamma rays to radio waves. Collectively, these wavelengths and frequencies make up the *electromagnetic spectrum,* as shown in figure 2-2. Here on earth, radar systems transform electrical energy into electromagnetic energy in the form of *radio waves.*

Each region of the electromagnetic spectrum can be subdivided into narrower *frequency bands* as shown in figure 2-2. As you can see, electromagnetic waves from radar energy normally fall between 200 MHz and 300 GHz. A radar transmitter emits this energy into the atmosphere through an antenna. While only a fragment of the energy returns, it provides a great deal of information. The entire process of energy propagating through space, striking objects, and returning occurs at the speed of light. Targets struck by electromagnetic energy are said to have been *radiated,* and the return signals they produce are called *radar echoes.*

PROPERTIES OF ELECTROMAGNETIC WAVES

An electromagnetic wave consists of two fields, an electrical field and a magnetic field, which are perpendicular to each other and to the direction of propagation of the wave front *(fig. 2-3). Polarization* refers to the orientation of the electrical field component of an electromagnetic wave. Polarization can be either linear or circular. With linear polarization, the electromagnetic waves are either horizontally or vertically polarized relative to the earth's surface (fig. 2-3).

Most weather radars, including the WSR-88D, are horizontally polarized. There are two major benefits to this. The first is that energy returns from man-made ground targets that have a greater vertical extent than horizontal extent (like buildings) are greatly reduced. The second benefit relates to the returned energy from raindrops. Since raindrops tend to flatten as they fall, the surface area that the radar is able to detect increases, thus increasing energy return. Other important terms relating to electromagnetic waves you need to know are wavelength, amplitude, frequency, and power.



Band Designation	Nominal Frequency	Nominal Wavelength
HF	3-30 MHz	100-10 m
VHF	30-300 MHz	10-1 m
UHF	300-1000 MHz	1-0.3 m
L	1-2 GHz	30-15 cm
S	2-4 GHz	15-8 cm
C	4-8 GHz	8-4 cm
X	8-12 GHz	4-2.5 cm
K_u	12-18 GHz	2.5-1.7 cm
K	18-27 GHz	1.7-1.2 cm
K_a	27-40 GHz	1.2-0.75 cm
mm	40-300 GHz	7.5-1 mm

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Figure 2-2.—The electromagnetic spectrum.

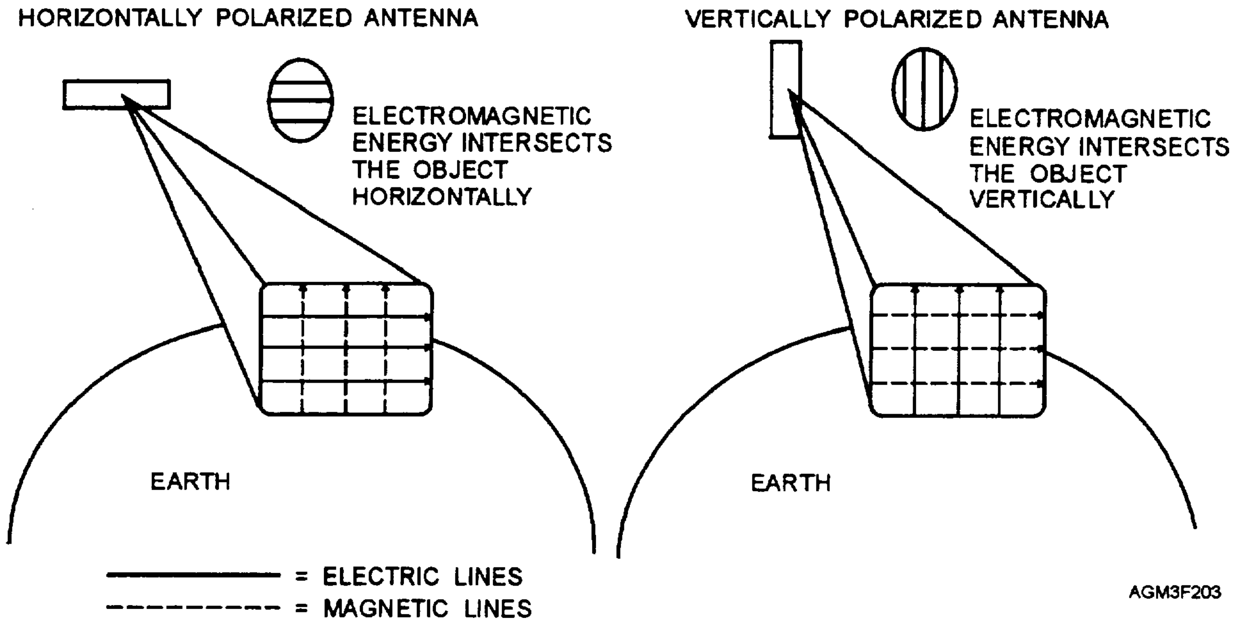

Figure 2-3.—Horizontally and vertically polarized electromagnetic waves.

Wavelength

The distance from wave crest to wave crest (or trough to trough) along an electromagnetic wave's direction of travel is called wavelength. Each measurement equals one complete wave, or wave cycle, and is typically expressed in centimeters. Each wavelength can also be described in terms of degrees, with one wavelength equal to 360° (fig. 2-4). This concept will become very important later, when we discuss Doppler radar.

As radar energy is emitted into the atmosphere, it encounters particles of dust, dirt, and salts, in addition to water vapor and precipitation. Collectively, these are known as scatterers, and they have an important effect on radar effectiveness. Wavelength plays a critical role in a weather radar's ability to see scatterers, that is, water droplets. Shorter wavelengths provide more detail and allow detection of small droplets, while longer wavelengths are best for larger targets, such as precipitation from rain showers and thunderstorms. It is important that a radar wavelength

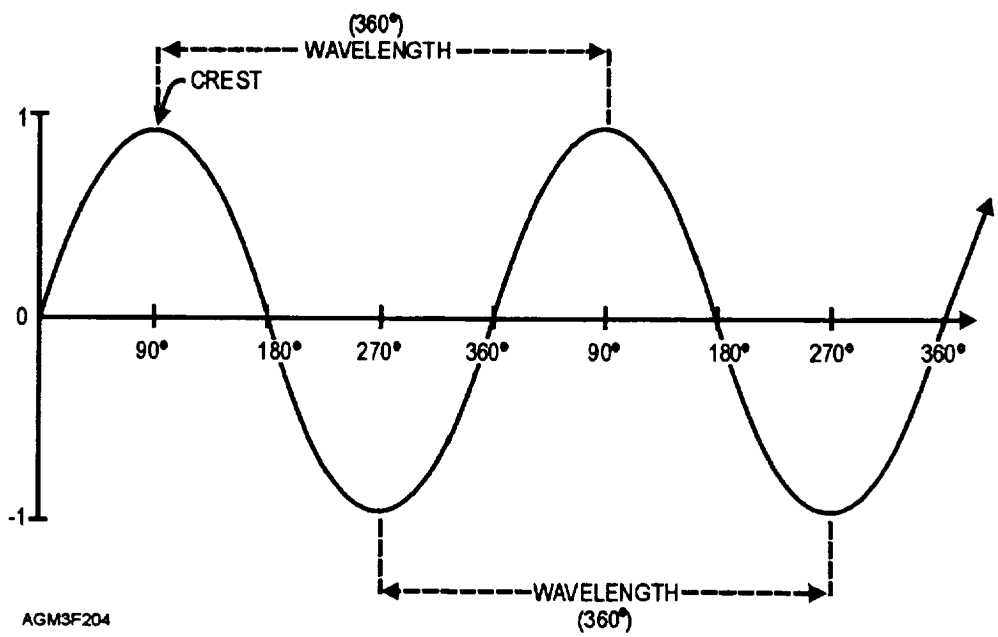

Figure 2-4.—Wavelength of an electromagnetic wave.

be short enough to detect fine scatterers without sacrificing severe weather detection abilities.

Amplitude

Wave *amplitude* is simply the wave's height (from the midline position) and represents the amount of energy or power contained within the wave. Simply put, greater amplitude means more power. Amplitude is usually expressed as some fraction of a meter (fig. 2-5).

Frequency

Frequency refers to the number of completed wave cycles per second. Radar frequency is expressed in units of hertz (Hz); one hertz being equal to one cycle per second. Frequency and wavelength are closely related as a change in one has a direct impact on the other. Essentially, higher frequency transmitters produce shorter wavelengths and lower frequency transmitters produce longer wavelengths. All wave characteristics in some way affect radar power. When more energy is available to strike targets, both signal strength and data reliability are increased and the radar performs more efficiently.

Electromagnetic waves can be described in terms of either frequency or wavelength. Looking back at figure 2-2, you can see the function of frequency versus wavelength.

Power

Power is the rate at which energy is used, With electromagnetic energy, the decibel system is used to compare two power values. A decibel, abbreviated "dB" is one tenth of a bel, the fundamental unit. The decibel system is useful for comparing power values that differ greatly, such as transmitter and receiver power. Values for dB are measured logarithmically, not linearly. With this in mind, you must be aware that every change of 3 dB corresponds to a *doubling (or halving)* of power. Doppler reflectivity values, which will be discussed later, are indicated by the abbreviation "dBZ."

REVIEW QUESTIONS

Q1. What is an electromagnetic wave?

Q2. Radar energy occupies what portion of the electromagnetic spectrum?

Q3. Wavelength is usually measured in what units?

Q4. How does wavelength affect a radar's ability to detect different types of targets?

Q5. Define radar frequency.

Q6. Given a frequency of 200 MHz and a frequency of 100 GHz, which one has a shorter wavelength?

Q7. How can different radar power values be compared?

BASIC RADAR CONFIGURATION

LEARNING OBJECTIVES: Define reflectivity. Identify the major parts of a radar system. Define radar sensitivity.

The acronym RADAR stands for RAdio Detection And Ranging. Radio waves, like light waves, are reflected from objects. The term *reflectivity* refers to the amount of energy returned from an object and is dependent on the size, shape, and composition of the

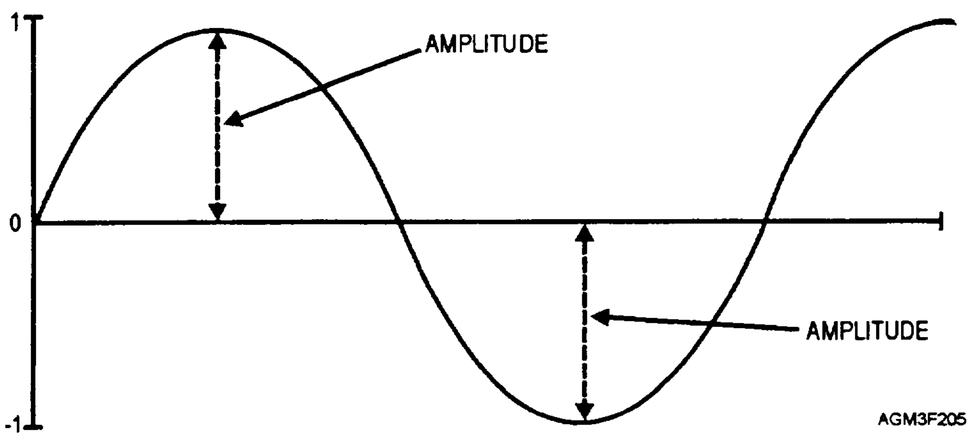

Figure 2-5.—Amplitude of an electromagnetic wave.

object. Through short bursts of radio EM energy, weather radar equipment displays the location and intensity (reflectivity) of meteorological targets such as rain showers and thunderstorms.

Figure 2-6 is a block diagram for a simple radar system that consists of the following components:

- A modulator that tells the transmitter when to transmit and for what duration.
- A transmitter that generates power.

An antenna that concentrates the radiated power into a shaped beam, which points in the desired direction and collects the echo signal for delivery to the receiver.

- A duplexer that connects the transmitter to the antenna during the transmission of the radiated pulse and connects the receiver to the antenna during the time between radiated pulses.
- A receiver that amplifies the weak echo signals picked up by the antenna to a level sufficient to display them.
- A signal processor that evaluates the signal from the receiver.
- A visual display unit that presents the information contained in the echo signal to an operator for interpretation.

Of prime importance concerning all these components is the radar's *sensitivity.* A radar's sensitivity, or signal to noise ratio, is a measure of the interference generated by the radar (self noise) against the minimum signal it is able to detect.

REVIEW QUESTIONS

Q8. What is meant by the term "reflectivity"?

Q9. Which part of a radar system shapes energy into a beam?

Q10. What is meant by the term "radar sensitivity "?

PRINCIPLES OF RADAR PROPAGATION

LEARNING OBJECTIVES: Distinguish various radar pulse characteristics, including pulse length, listening time, range ambiguity, range folding, and pulse volume. Define range resolution and pulse repetition frequency. Compute Rmax. Recognize the effects of beamwidth, beam broadening, and sidelobes on radar energy. Define azimuthal and range resolution.

Rather than transmit one long continuous wave (CW), weather radar uses short, powerful bursts of energy called pulses. Pulsed energy travels along a focused path called a beam, and occupies a specific amount of space. Pulses are separated by silent periods that allow the antenna to listen for a return pulse. The information gained from these pulses is critical in

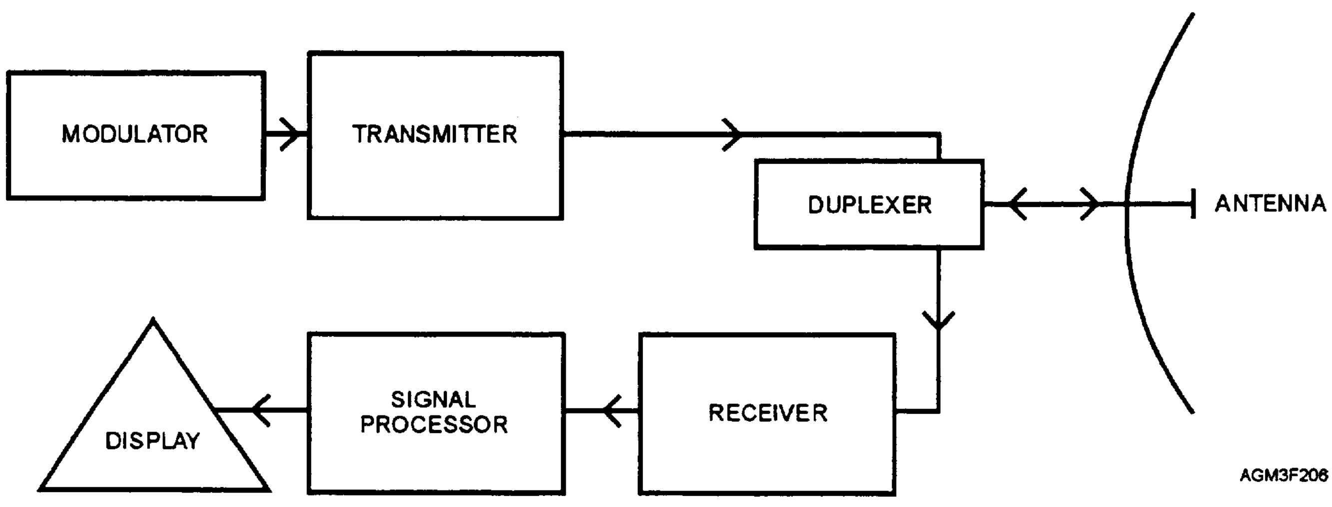

Figure 2-6.—Block diagram for a simple radar system.

determining target size, strength, and location (fig. 2-7).

RADAR PULSE CHARACTERISTICS

Radar pulses travel at the speed of light (186,000 miles per second). Thus, the distance to a target can easily be calculated by monitoring a pulse's elapsed time from transmission until its return. Half the distance traveled by the pulse determines the target's range from the antenna.

Pulse Length

Pulse length (or pulse duration) is the measurement taken from the leading to trailing edge of a pulse and is a good indicator of the amount of power contained within the pulse (fig. 2-7). Generally, longer pulses emitted from a radar return more power, thus increased target information and data reliability. Longer pulses have the disadvantage in that fine details within the return echo may be lost. Pulse length is usually expressed in microseconds, but is also measured in kilometers. The WSR-88D incorporates a variable pulse length that may be as short as 1.57 microseconds (1,545 feet). Important aspects ofaradar pulse include minimum range, range resolution, and pulse repetition frequency.

MINIMUM RANGE.—Pulse length determines a radar's minimum range or how close a target can get to the antenna without adversely affecting operations. Minimum radar range is defined as any distance greater than one-half the pulse length. In other words, targets more than one-half pulse length from the antenna can be correctly processed, while approaching targets that get too close pose serious problems. If targets come within one-half pulse length or less of the antenna, the pulse's leading edge will strike the target and return **before** the radar can switch into its receive mode. Some portion of the return energy is lost and the radar may become confused and discard the pulse.

RANGE RESOLUTION.—A radar's resolution is its ability to display multiple targets clearly and separately. Range resolution refers to targets oriented along the beam axis as viewed from the antenna's position. Longer pulses have poorer range resolution. Targets too close together lose definition and become blurred. They must be more than one-half pulse length apart or they will occupy the pulse simultaneously and appear as a single target. The problem of range resolution will be discussed in more detail later.

PULSE REPETITION FREQUENCY (PRF).—PRF is the **rate** at which pulses are transmitted (per second). It controls a radar's maximum effective range by dictating the duration of its listening time. Increased PRF speeds the rate at which targets are repeatedly radiated. This increased sampling results in greater target detail, but the maximum range of the radar is reduced because of the shorter periods between pulses. The WSR-88D can emit anywhere from 318 to 1304 pulses per second. It has a maximum range of approximately 250 nautical miles (nmi).

Listening Time

Following the transmission of each pulse, the radar switches to receive mode awaiting its return. This break in transmission is appropriately called "listening time." When pulses do not return during their prescribed listening time, the radar assumes no targets were encountered and that the pulse has continued on its outward direction.

Listening time determines a radar's maximum effective range as it, in effect, limits the distance a pulse can travel. If listening time is reduced, pulses can cover less distance and effective range is decreased. Thus, a 50-percent reduction in listening time cuts maximum radar range in half. Only targets within the maximum effective range are detectable.

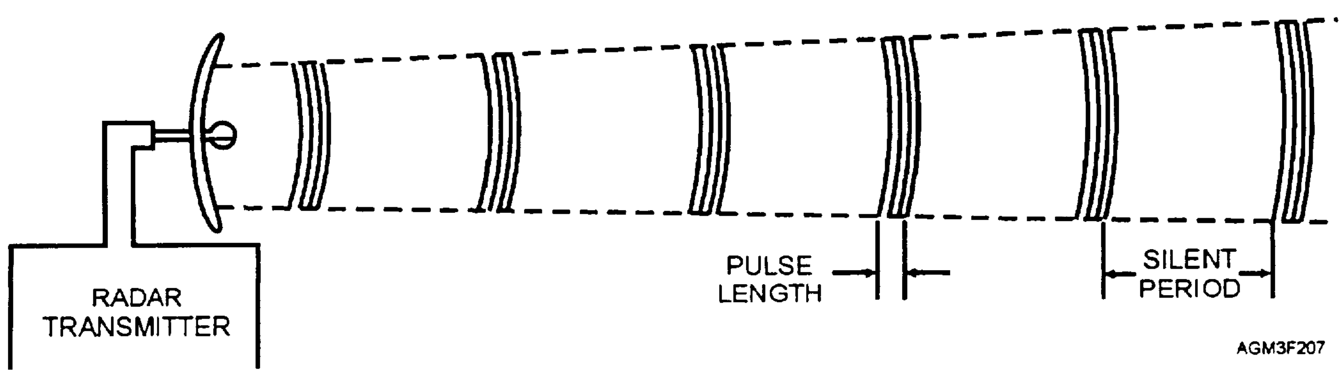

Figure 2-7.—Radar Pulses

Range Ambiguity

As described earlier, the pulse repetition frequency largely determines the maximum range of the radar set. If the period between successive pulses is too short, an echo from a distant target may return after the transmitter has emitted another pulse. This would make it impossible to tell whether the observed pulse is the echo of the pulse just transmitted or the echo of the preceding pulse. This produces a situation referred to as *range ambiguity*. The radar is unable to distinguish between pulses, and derives range information that is ambiguous (unreliable).

In theory, it is best to strike a target with as many pulses of energy as possible during a given scan. Thus, the higher the PRF the better. A high PRF improves resolution and range accuracy by sampling the position of the target more often. Since PRF can limit maximum range, a compromise is reached by selectively increasing the PRF at shorter ranges to obtain the desired accuracy of measurements.

The *maximum unambiguous range (Rmax)* is the longest range to which a transmitted pulse can travel and return to the radar before the next pulse is transmitted. In other words, *Rmax* is the maximum distance radar energy can travel round trip between pulses and still produce reliable information. The relationship between the PRF and Rmax determines the unambiguous range of the radar. The greater the PRF (pulses per second), the shorter the maximum unambiguous range (Rmax) of the radar. The maximum unambiguous range of any pulse radar can be computed with the formula: Rmax = c/(2xPRF), where *c* equals the speed of light (186,000 miles per second). Thus, the maximum unambiguous range of a radar with a PRF of 318 would be 292 miles (254 nmi), 186,000/2 x 318 = 292. The factor of 2 in the formula accounts for the pulse traveling to the target and then back to the radar.

Range Folding

While it's true that only targets within a radar's normal range are detected, there are exceptions. Occasionally, a pulse strikes a target outside of normal range and returns during the next pulse's listening time. This poses a complex problem known as *range folding.* Range folding may cause operators to base crucial decisions on false echoes. The data received from this stray pulse could be misanalyzed and echoes may be plotted where nothing exists. The data may look reliable and the radar may appear to be functioning properly, adding to the deception of normal operation.

Refer to figure 2-8. Assume a pulse was emitted during the radar's previous scan. While it travels beyond normal range and strikes a target, the radar emits a second pulse. Since no targets exist within normal radar range, these pulses will pass each other in flight. The first pulse now returns while the radar is expecting the second pulse (during the listening time of the second pulse). The radar believes that the second pulse has struck a target 124 nmi from the antenna and displays. an echo accordingly (target "X"). The operator is fooled by target "X" and issues a severe weather warning, when in fact, no clouds are present. Target "X" was an illusion, a reflection of a thunderstorm located 372 nmi from the antenna. Fortunately, the WSR-88D is equipped with a range unfolding mechanism that attempts to position all echoes properly.

Pulse Volume

As pulses travel they look like a cone with its point cut off (fig. 2-9). They expand with the beam and increase in volume. The volume of a pulse is the space

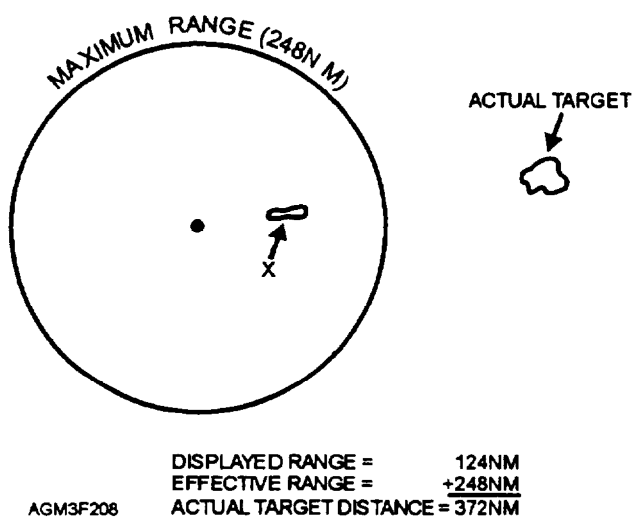

Figure 2-8.—Radar range folding.

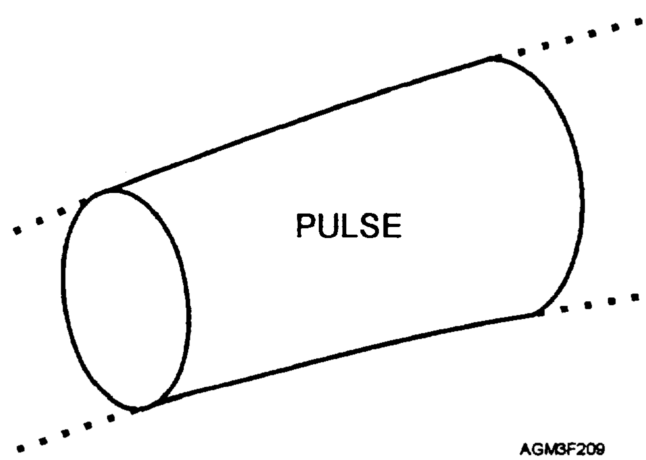

Figure 2-9.—Radar pulse volume. Pulse volume increases with distance from the antenna as the pulse expands in all directions.

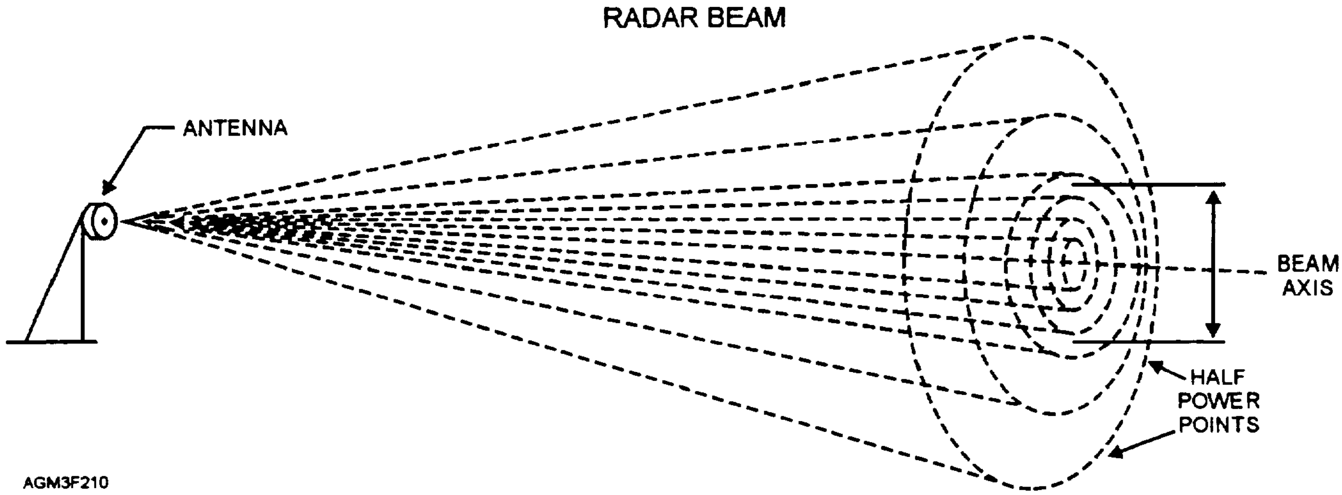

Figure 2-10.—Half-power points and beamwidth.

it occupies along the beam at any point in time. Unlike pulse length, volume does not remain constant. While the amount of power within a pulse is determined by its length and remains constant, power density **decreases** with distance. This occurs because the pulse's fixed amount of energy is spread over a greater area (pulse volume) as the beam broadens. The further a pulse travels, the weaker and less effective it becomes due to increased pulse volume.

RADAR BEAM CHARACTERISTICS

The characteristics of a radar beam refer to **beamwidth, beam broadening,** and the presence of **sidelobes.**

Beamwidth

Since EM energy contains properties similar to light, it can be pointed and controlled much like a flashlight. A suitable antenna can easily focus it into a beam and direct its movement. A radar beam is the path that guides a pulse's travel. Energy emitted into the atmosphere remains concentrated along the beam axis. As you move outward at right angles to this axis, power density gradually decreases. At some point, power density equals one-half of that found at the beam axis. These *half-power points* wrap completely around the beam and define its shape in terms of height and width, or more appropriately, its circumference. The area within these half-power points is defined as the **beam,** and it contains nearly 80 percent of all energy (fig. 2-10). The angular distance between half-powerpoints in a plane passing through the beam centerline is the beamwidth. Beamwidth varies directly with wavelength and inversely with antenna size. Radar systems that produce relatively small beam widths generally provide greater target resolution.

Beam Broadening

As pulses travel away from the antenna, the beam takes on a cone-like appearance and expands in all directions. This expansion or *beam broadening* increases pulse volume, resulting in decreased signal strength (fig. 2-11). Distant targets appear distorted, in fact, they may not be seen at all. Beam broadening also causes "partial beam filling," which implies that distant targets occupy proportionally less of an expanded beam. Thus, the true characteristics of a target may be hidden or altered during display.

Beam broadening reduces azimuthal resolution and produces a form of radar nearsightedness. As the beam diameter increases with distance, closely spaced targets may occupy the beam simultaneously and

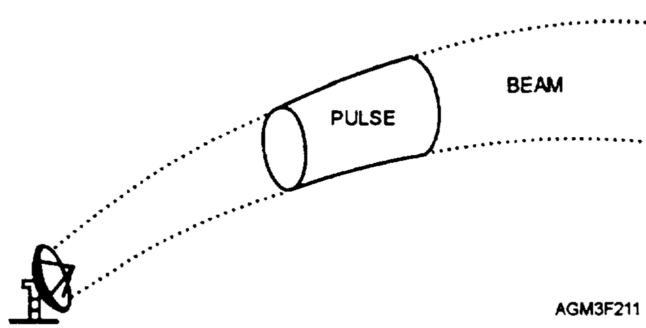

Figure 2-11.—Radar beam broadening.

appear as one echo. In short, multiple targets at a distance are difficult to see correctly.

Sidelobes

In addition to the main beam, antennas produce rays of energy called *sidelobes,* which surround the main beam (primary lobe) like haloes (fig. 2-12). Sidelobes extend outward only a short distance from the radar and contain very low power densities. However, even though they are weak, sidelobes can detect strong non-meteorological targets near the radar and are also disturbed by nearby g-round reflections. This leads to confusion in interpreting close targets because sidelobe targets are displayed along with the main beam targets.

RADAR RESOLUTION

Radar resolution is the radar's ability to display targets correctly. Both azimuthal resolution and range resolution are problems that commonly effect all radars. Recall our earlier discussion about distant objects and their distorted appearance. Resolution affects radar much the same way.

Azimuthal Resolution

Azimuthal resolution is often called bearing or directional resolution. It is a radar's ability to display side-by-side targets correctly. Azimuthal resolution is controlled by beam width as only targets separated by more than one beamwidth can be displayed separately.

As the radar antenna rotates, targets too close together occupy the beam simultaneously. This causes them to be displayed as one wide target, stretched azimuthally (sideways). Since azimuthal resolution depends on beamwidth, which changes with distance, targets near the antenna require less separation than those further out. Near the antenna, a narrower beam allows the radar to recognize tighter gaps and display targets separately. At greater distances, more separation is required. If targets are not separated by the prescribed amount, distortion occurs and resolution suffers. With the WSR-88D, azimuth distortion is approximately 1 mile at a 50-nmi range. Thus, at 250 nmi, two targets must be about 5 miles apart before they will appear as two separate targets.

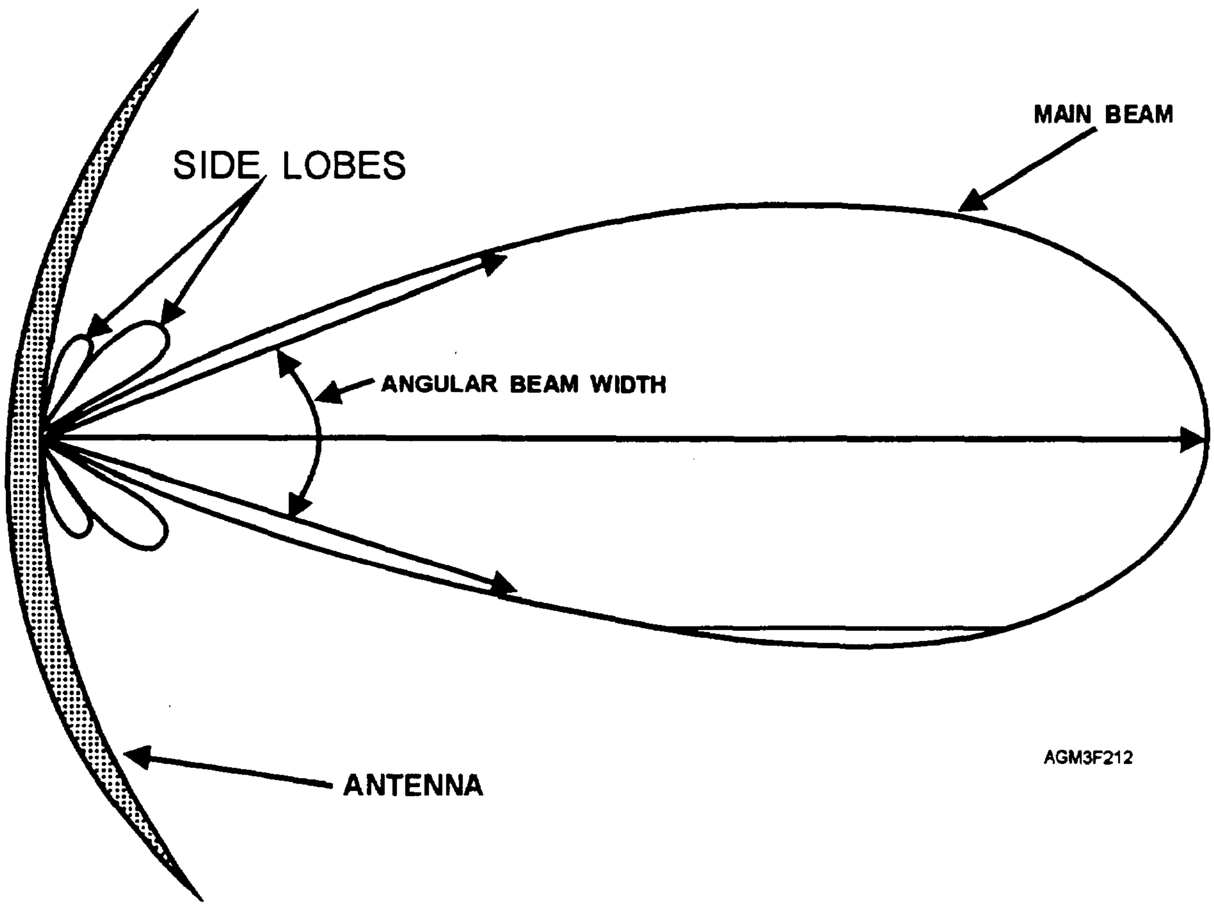

Figure 2-12.—Radar sidelobes.

In figure 2-13, notice that targets located at position "A" are more than one beamwidth apart. The radar therefore displays them correctly, as two separate echoes. Also notice that some degree of stretching is evident, in both echoes, due to partial beam filling. Targets located at position "B" are exactly one beamwidth apart and are displayed as one large echo. As the beam rotates, there is no break in returned energy between targets. As their energy is merged, they appear to occupy the entire beam. Position "C" illustrates poor azimuthal resolution and target stretching caused by partial beam filling.

Range Resolution

Range resolution is the radar's ability to display in-line targets separately. Range resolution affects targets along the beam, oriented behind one another. Targets must be more than one-half pulse length apart or they occupy the pulse together; their returned energy is merged making it impossible for the radar to see their separation. Targets too close together appear as one and are displayed accordingly (stretched along the beam axis). Range resolution is solely a function of pulse length.

Pulse length is unaffected by distance, therefore separation criteria remains constant.

In figure 2-14, a radar pulse is approaching two objects (targets) that are one-half pulse length apart (view A). In view (B), the pulse has hit the first target and some of the energy is reflected back to the radar. In view (C), the pulse has just reached the second target and more energy is reflected back to the radar from the first target. In view (D), the pulse strikes the second target and energy is now reflected back from that target: In view (E), reflected energy from the first target continues to reflect towards the radar along with the second target, which is now one-half pulse length long. Its "front end' is nearly coincident with the first target. From this, we learn why it's impossible for the radar to tell where one pulse ends and another begins. The radar sees one continuous signal. The slightest increase in target separation will overcome this limitation and enable the radar to display both targets correctly.

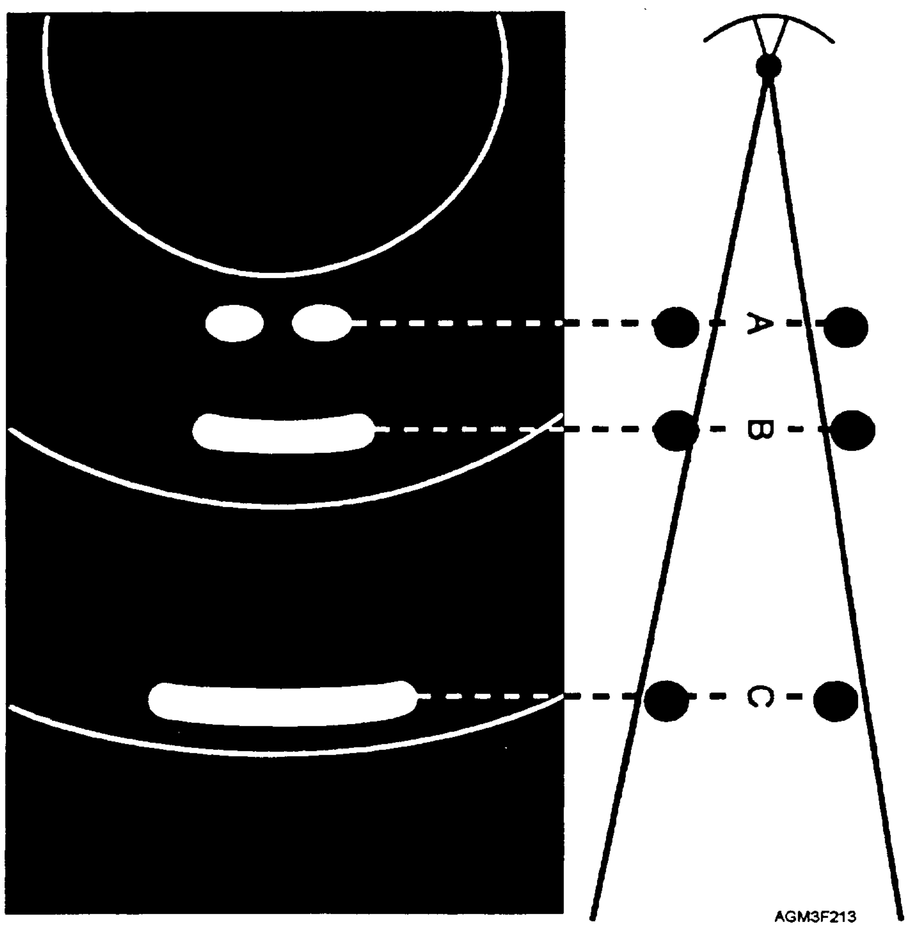

Figure 2-13.—Azimuthal resolution and target stretching.

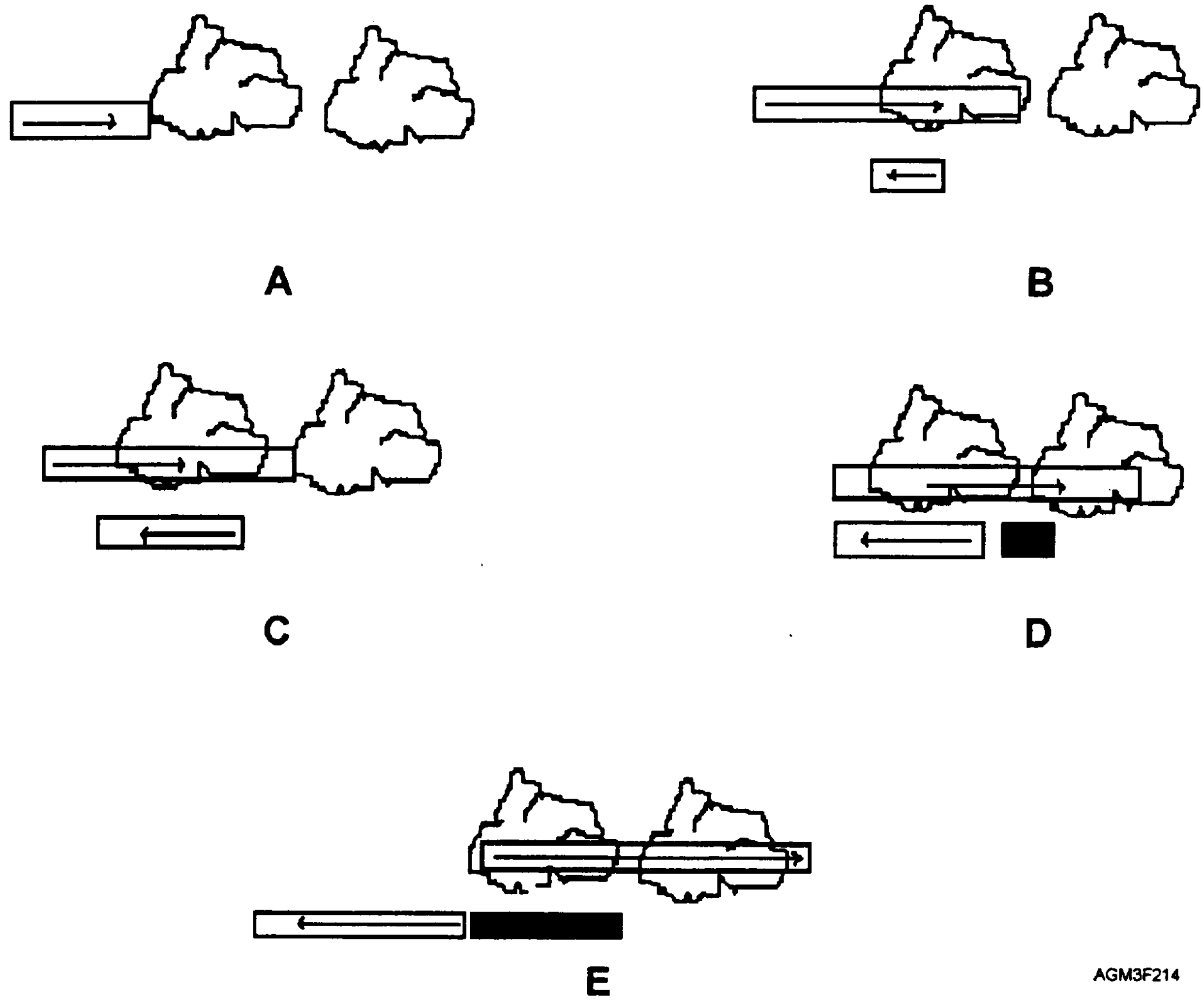

Figure 2-14.—Pulse length versus range resolution.

REVIEW QUESTIONS

Q11. How does pulse length affect the amount of energy returned from each pulse?

Q12. Pulse length is usually measured in what units?

Q13. What is described by the term "resolution"?

Q14. What is a radar's ‘pulse repetition frequency"?

Q15. What happens when a radar's PBF is increased?

Q16. What is meant by the term "range ambiguity"?

Q17. If a radar had a pulse repetition frequency (PRF) of 1000, what would be its maximum unambiguous range?

Q18. What causes the phenomena of range folding?

Q19. How does pulse volume affect radar power?

Q20. Which beamwidth would provide better target resolution, a large beamwidth or a small beamwidth?

Q21. What is the effect of beam broadening on radar pulses?

Q22. How does the presence of sidelobes affect radar performance?

Q23. What is the main cause of degraded azimuthal resolution?

Q24. What is the main radar characteristic affecting range resolution?

FACTORS AFFECTING RADAR PROPAGATION

LEARNING OBJECTIVES: Define refraction and refractive index. Recognize the effects of refractivity on radar systems. Identify effects of subrefraction, superrefraction, and ducting on radar systems. Define and identify effects of diffraction and ground clutter on radar systems. Identify effects of scattering, absorption, and solar activity on radar systems.

As a radar pulse travels through the atmosphere, various physical actions cause the energy of the pulse to decrease. In this section, we will describe these physical actions and their effect on radar systems.

REFRACTION

A common misconception about a radar beam is that it travels in a straight line, much like that of a laser beam. In reality, the beam (electromagnetic wave) is actually bent due to differences in atmospheric density. These density differences, both vertical and horizontal, affect the speed and direction of electromagnetic waves. In some regions, a wave may speed up, while in other regions it may slow down. When one portion of a wave is slowed and another portion is not, the wave bends in the direction of the **slower** portion of the wave. This bending is known as *refraction.* Refraction in the atmosphere is ultimately caused by variations in temperature, moisture, and pressure, with changes in moisture having the greatest impact.

Refractive Index and Refractivity

In free space, an electromagnetic wave will travel in a straight line because the velocity of the wave is the same everywhere. The ratio of the distance a wave would travel in free space to the distance it actually travels in the earth's atmosphere is called the *refractive index. The* refractive index is symbolized by "n" and a typical value at the earths surface would be 1.000300. Thus, "n" would gradually decrease to 1.000000 as you move upward toward the theoretical interface between the atmosphere and free space. For example, in the time it takes for electromagnetic energy to travel a distance of one wavelength in air at 1000 hPa, 15°C temperature, and 40 percent relative humidity, it could have traveled 1.0003 wavelengths in free space, which makes 1.0003 the refractive index. The normal value of n for the atmosphere near the earths surface varies between 1.000250 and 1.000400.

Since the refractive index produces a somewhat unwieldy number, we use a scaled refractive index called *refractivity.* Refractivity is symbolized by "N" and is a function of pressure, temperature, and vapor pressure (moisture). A result is that atmospheric refractivity near the earth's surface normally varies between 250 and 400 N units (the smaller the N-value, the faster the propagation; the larger the N-value, the slower the propagation). Refractivity values become smaller with decreasing pressure and decreasing moisture, but larger with decreasing temperature. All of these variables usually decrease with increasing altitude. However, the increase in N due to decreasing temperature is not sufficient to offset the decrease in N due to a decrease in moisture and pressure. As a result, refractivity values will normally **decrease** with increasing height.

NOTE: It is sometimes advantageous to compute refractivity in terms of waves traveling in a straight line. This may be approximated by replacing the actual earth's radius (curved earth) with one approximately four-thirds as great ("flat earth"). The refractivity using this orientation is called *modified refractivity* and is expressed in *M units.*

Several software programs such as GFMPL automatically compute N-units and M-units from radiosonde data. N-units can also be computed from a special Skew-T, Log P diagram with a refractivity overprint (DOD-WPC 19-16-2). A refractivity nomogram, such as the one in Appendix II, can also be used.

Refractive Conditions

Under normal atmospheric conditions, when there is a gradual decrease of pressure, temperature, and humidity with height, a radar beam's curvature is slightly less than the earth's curvature. This causes it to gradually climb higher with distance and is called standard or *normal refraction* (fig. 2-15, view A). When there is an unusual or other-than-normal vertical distributions of moisture and/or temperature, nonstandard refraction or *anomalous propagation (AP)* takes place. This causes exaggerated bending of the beam either up or down. There are three categories of anomalous propagation: subrefraction, superrefraction, and ducting.

SUBREFRACTION.—Occasionally, motions in the atmosphere produce a situation where the temperature and humidity distributions create an **increasing** value of N with height. This occurs when density contrast in the atmosphere is weak, such as when water vapor content increases and/or temperature decreases rapidly with height. The beam bends less than normal and climbs excessively skyward. This phenomenon is known as *subrefraction.* Subrefraction causes the radar to overshoot targets that are normally detected (fig. 2-15, view B). Subrefractive conditions are generally rare, and usually occur in desert regions and on the lee sides of mountain ranges.